



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Plans for Ignition Experiments on NIF

E. Moses

August 6, 2007

7th Symposium on Current Trends in International Fusion
Research
Washington, DC, United States
March 5, 2007 through March 9, 2007

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

PLANS FOR IGNITION EXPERIMENTS ON THE NATIONAL IGNITION FACILITY

Edward I. Moses

Lawrence Livermore National Laboratory
Livermore, CA 94551 U.S.A.

ABSTRACT

The National Ignition Facility (NIF) is a 192-beam Nd-glass laser facility presently under construction at Lawrence Livermore National Laboratory (LLNL) in support of inertial confinement fusion (ICF) and high-energy-density (HED) science. NIF will produce 1.8 MJ, 500 TW of ultraviolet light, making it the world's largest and most powerful laser system. NIF will be the world's preeminent facility for the study of matter at extreme temperatures and densities and for producing and developing ICF. The ignition studies will be the next important step in developing inertial fusion energy.

1. INTRODUCTION

The NIF Project is over 90% complete and scheduled for completion in 2009. The building and nearly the entire beam path have been completed. Fig. 1 shows the beam path in one of the two laser bays. The Project is presently installing the optics and electronics and commissioning the beams. Over half the optical and electronics components needed to complete the Project have been installed. One cluster of 48 beams has been commissioned in the laser bay with the demonstrated capability of producing 1000 kJ of 1053 nm light (1 W), nearly ten times the capability of Nova or Omega, the previous largest laser systems. In addition, experiments using one beam have demonstrated that NIF can meet all of its performance goals.

Current Trends in International Fusion Research — Proceeding of the Seventh Symposium, Edited by Emilio Panarella and Roger Raman. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6 Canada, 2007.



Figure 1. View of one of the laser bays showing two clusters of 48 beams.

2. NATIONAL IGNITION CAMPAIGN

A detailed plan called the National Ignition Campaign (NIC) has been developed to begin ignition experiments in 2010. NIC is a collaborative effort involving LLNL, the University of Rochester Laboratory for Laser Energetics, General Atomics, Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). Components of the NIC plan include target physics, systems engineering and operations as well as targets, and equipment such as target diagnostics, cryogenic target positioner, and user optics required for the ignition experiment. Target designs have been developed that calculate to ignite at energy of approximately 1 MJ. An example of a calculation of an igniting capsule is shown in Fig. 2.

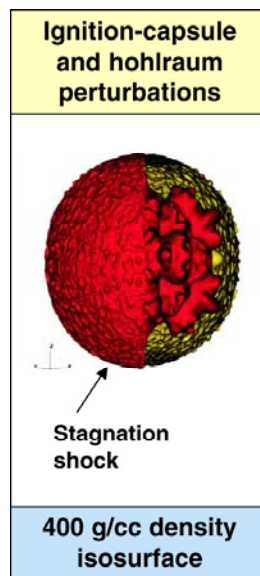


Figure 2. Iso-density surface of a 3-d calculation of an igniting capsule.

Experiments using the OMEGA laser at the University of Rochester are helping to validate these designs. Development of manufacturing capability is well under way for producing these targets to the required tolerances. Diagnostics and other support equipment is being designed and fabricated to perform the ignition experiments.

The NIF Project and NIC activities are merging at a rapid rate. The NIF laser and the equipment needed for ignition experiments, including high-quality targets, will be available in March, 2009. In less than a year we will be commissioning laser beams to the target chamber (Fig. 3). We have planned a campaign with 96 beams in July 2008, called “Early Opportunity Shots” or EOS, which will allow us to choose the optimum hohlraum temperature and laser energy for initial ignition experiments. EOS is a fitting name because NIF represents the dawn of a new era in physics research, especially in the field of HED science.

The Laser Plasma Interaction (LPI) uncertainty in the ignition-point design is bounded by about 300 kJ in laser energy or by a range of hohlraum temperatures of 270–300 eV. Starting with this EOS series, NIF will be established as a preeminent international HED physics facility and set the facility directly on the path to the first ignition experiments in 2010. The initial ignition experiments only scratch the surface of NIF’s potential, which includes high yields with green light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition in Fast Ignition (FI).

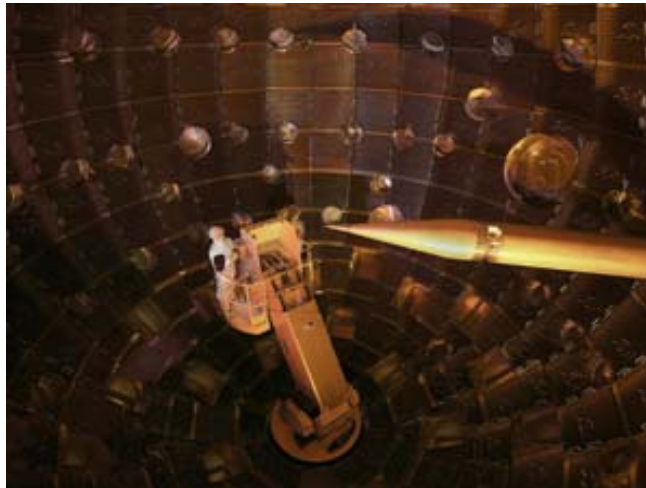


Figure 3. The NIF target chamber is constructed from 4-inch-thick aluminum and coated with a 16-inch-thick neutron shielding concrete shell. The entire assembly weighs about one million pounds. The target positioner, which holds the target at its tip, is on the right.

NIF produces pulses lasting from 0.2 to 10s of nanoseconds. During recent tests in the Precision Diagnostic Station (PDS) all of NIF performance requirements have been demonstrated on a single-beam basis. These tests demonstrated NIF’s capabilities for HED experiments in support of the Department of Energy’s (DOE’s) Stockpile Stewardship Program and for basic science experiments to explore such topics as the origin and makeup of the planets and the hydrodynamics of supernovae—explosions of massive stars.

The modular control system concept dovetails well with plans for NIF experiments. For example, although achieving ignition will require all 192 beams, many experiments will require fewer laser beams. Each NIF experimental series will require different laser

parameters such as wavelength, energy, and pulse duration; different configurations of the laser beam; different laser targets; and different diagnostic instruments. By taking advantage of the facility's experimental flexibility, teams will be able to create an extraordinary range of physical environments, including densities ranging from one-millionth the density of air to ten times the density of the core of the sun, temperatures ranging from a terrestrial lightning bolt (about 10^4 K) to the core of a carbon-burning star (10^9 K) and pressures from 1 to 100 TPa (1 gigabar). Researchers will study phenomena at timescales ranging from fractions of a microsecond (10^{-6} s) to picoseconds (10^{-12} s).

3. EXPLORING FRONTIER SCIENCE

In addition to supporting of the Department of Energy's (DOE) Stockpile Stewardship Program, NIF will provide researchers from universities and DOE national laboratories unparalleled opportunities to explore "frontier" basic science in astrophysics, planetary physics, hydrodynamics, nonlinear optical physics, and materials science. About 15% of NIF shots will be devoted to science experiments in these fields. The first science studies will focus on re-creating in the laboratory the properties of celestial objects under scaled conditions. With its 192 beams together generating up to 1.8 MJ of energy, the giant laser will allow scientists to explore some of the most extreme conditions in the universe such as the hot, dense plasmas found in stars.

NIF experiments will help scientists understand the mechanisms driving new stars, supernovae, black holes, and the interiors of giant planets. The physical processes of stars have long been of interest to LLNL researchers because the prime stellar energy mechanism, thermonuclear fusion, is central to the Laboratory's national security mission. For decades, researchers have advanced astrophysics by applying their expertise in HED physics and computer modeling of the nuclear processes that take place in these regimes.

Once NIF attains ignition (a burst of fusion reactions in which more energy is liberated than is input), a flux of 10^{32} to 10^{33} neutrons per square centimeter per second will be generated, a rate that may allow excited-state nuclear reactions to occur. This neutron flux will also enable scientists to extend their understanding of the nucleosynthesis of heavy elements, those nuclei more massive than iron. Scaled NIF experiments will permit studies of the entire life cycle of a star, from its birth in a cold, dense molecular cloud through its subsequent stages of evolution to an explosive death such as a supernova.

Once formed, stars are heated by nuclear fusion in the interior and cooled by radiation emissions at their surface, called the photosphere. Opacities of each layer control the rate at which heat moves from the core to the surface. In this way, opacity plays a major role in determining the evolution, luminosity, and instabilities of stars. Experiments will mimic stellar plasma to obtain information on the opacities of key elements such as iron and determine how opacity changes with plasma density and temperature throughout a star's lifetime. Experimenters plan to simultaneously measure the radiation transmission, temperature, and density of a material sample.

4. TARGETS FOR IGNITION

All of these experiments have one common requirement: a centimeter-scale target, precisely centered in the target chamber. Creating a NIF target is a complex interplay among target designers, materials scientists, and engineers. Designers understand the goals for each experiment and must establish specifications for the target. NIF targets are typically only a few millimeters in size, and their complicated shapes must be machined to meet precise requirements, including specifications for density, concentricity, and surface smoothness.

Targets for the ICF experiments are being fine tuned by a large collaboration that includes scientists and engineers from LLNL, General Atomics in San Diego, the University of Rochester's Laboratory for Laser Energetics and LANL. This team is perfecting the target materials and methods to fabricate them. Nanoscale materials developed for NIF experiments include high-density carbon, very low-density copper and gold foams, and graded-density foams.

Manufacturing requirements for all NIF targets are extremely rigid. Components must be machined to within an accuracy of 1 μm , or one-millionth of a meter. Joints can be as small as 100 nm, which is just one-thousandth the width of a human hair. In addition, the margin of error for target assembly is less than 8 μm . The extreme temperatures and pressures the targets will encounter during experiments make the results highly susceptible to imperfections in fabrication.

The current design for the ICF target is a copper-doped beryllium capsule with a smooth solid layer of the hydrogen isotopes deuterium and tritium (D-T) on its inner surface. The radially tailored capsule is made of a lightweight material (Fig. 4) and fits inside a 9-mm-high by 5-mm-wide hohlraum cylinder made of a material with a high atomic number such as gold (Fig. 5).

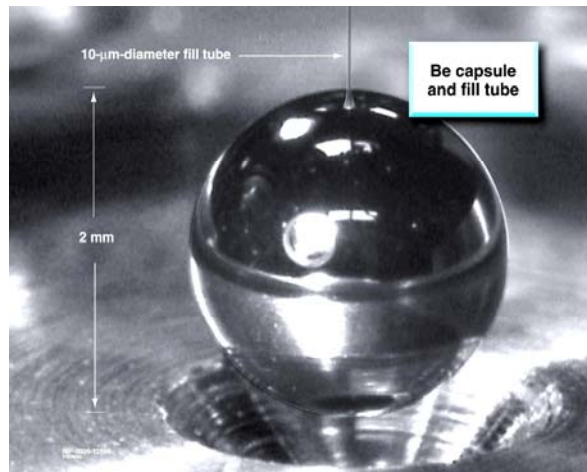


Figure 4. Beryllium capsule and fill tube.

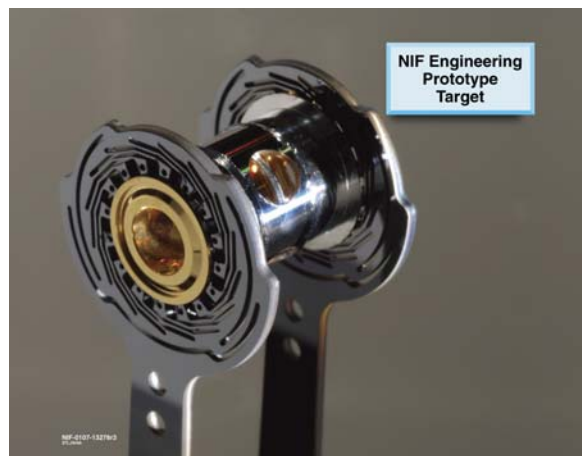


Figure 5. NIF Cryogenic Target.

When NIF's laser beams impinge on the hohlraum's inner cavity, laser energy is converted to x-ray energy. These x rays bathe the capsule and ablate its outer layer. Conservation of momentum requires that the remaining material implode or compress. Compressing the D-T fuel to extraordinarily high temperature, pressure, and density ignites a burning hydrogen plasma.

For NIF to achieve ignition, the beryllium capsule must have a precise spherical shape. The capsule's surfaces must be smooth to within 1 nm—an unprecedented requirement for surface roughness—and the thickness and opacity of the copper-doped layers must be carefully controlled. Each capsule is made by depositing beryllium on a smooth, perfectly spherical plastic mandrel. As the mandrel is rotated, a 150- μm -thick layer of beryllium slowly builds up on its surface. After a capsule is polished, a laser is used to drill a 5- μm fill hole. An oxidation technique removes the mandrel through the drilled hole, and a 10- μm tube is attached to the capsule so it can be filled with D-T gas.

5. CRYOGENIC FUEL

Researchers at LLNL, LANL and LLE have pioneered procedures to form the frigid layer of D-T fuel inside the fuel capsule. The D-T ice is 1.5 degrees below the triple point of the hydrogen isotope mixture—the temperature at which all three phases of the substance can coexist in equilibrium. Temperature can fluctuate no more than 1 mK—a demanding requirement for accuracy. Beta decay of the tritium helps smooth the layer by selectively heating thicker regions and evaporating hydrogen from them. NIF researchers found that the D-T ice can be shaped by precisely controlling heat transfer within the hohlraum, including contributions from thermal convection of helium. Auxiliary heaters located on the hohlraum shape the temperature field within the target to produce a nearly spherical isotherm. To control the ice layer's surface roughness, the NIF team developed a seeding and cooling protocol. The seeding process forms the initial layer, and cooling reduces its temperature from the triple point. With this protocol, the team achieved a roughness of about 0.5 μm (root mean square) at the interface where solid D-T meets D-T gas. A thermomechanical package encases the hohlraum to accurately control the position and temperature of the hohlraum-capsule assembly.

The thermomechanical package is a modular design with a precisely fabricated aluminum structure on each end. A band in the middle of the package has cutouts to accommodate the shot diagnostics. Silicon “arms” attached to each end of the package conduct heat from the hohlraum. These lithographically etched support arms create a heat-transfer path that ensures temperature uniformity in the target. In addition, a flexure coupling between the silicon arms and the aluminum structure accommodates differential thermal contraction. With the thermomechanical package, the target assembly can maintain its position to within 2 μm , and at 18 to 20 K, temperature fluctuations are limited to only 1 mK. This system integrates the ICF target with a cryogenic layering and characterization station and a target positioner attached to NIF's target chamber. The system includes a positioning boom to center the target in the chamber. An ignition-target inserter cryostat attached to the positioner cools the target and the D-T fuel to meet temperature and uniformity requirements. The layering and characterization station can image the D-T fuel layer in three directions within a few minutes.

6. CONCLUSION

NIF represents bold and courageous thinking. All prior large laser facilities were designed and built with the latest technologies and scientists then determined what research the facility could accomplish. In contrast, NIF was designed specifically to meet the needs of

three missions: strengthen stockpile stewardship for a safe and reliable nuclear stockpile, advance ICF as a clean source of energy, and make significant strides in HED physics.

These three missions share the need to expose materials to extraordinarily high pressures, temperatures, and densities—as much as 100 billion atmospheres pressure, 100 million degrees Centigrade temperature, and 1,000 g/cm³ density. These conditions occur in exploding nuclear weapons, in supernovae, and in the fusion reactions that power our Sun and other stars and that may one day provide an inexhaustible power supply on Earth. Because of the similarities of these phenomena, the results of some NIF experiments will be applicable to all three missions.

We cannot venture inside stars, planets, or black holes, nor can we traverse billions of light years across the universe to examine a supernova explosion. However, with NIF, we can re-create, on a vastly smaller scale, the same physical processes that astronomers can only glimpse through a telescope. 2010 marks the golden anniversary of the demonstration of the first laser and the concept of ICF. Our goal with the National Ignition Campaign is to demonstrate ignition and burn, in turn launching a new era of high energy density science and energy research. This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.